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WATER-YIELD IMPROVEMENT FROM ALPINE AREAS: The Status of Our Knowledge

M. Martinelli, Jr.

Abstract

Snowpack management can be an effective means of improving water yields from the already productive alpine type. Due to wind and rugged terrain, the alpine snowpack is characterized by deep snowfields and bare spots. Because snow accumulates in the lee of terrain breaks or other obstacles that provide wind protection, fences upwind of natural accumulation areas effectively trap additional snow. Snowfences can also control blowing and drifting snow on highways and in avalanche-prone areas. Factors that influence the efficiency of snowfences are: (1) height, (2) density and length of fence, (3) bottom gap, (4) length and maximum depth of lee drift, (5) cumulative effect of a set of tandem fences, (6) vertical alinement, (7) terrain effects, and (8) contributing distance.

Keywords: Alpine zone, water yield, snowfences, snowpack.

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[1]Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University.

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Introduction

The demand for water in semiarid areas has always exceeded the readily available supply. This problem tends to become critical in local areas during periods of rapid population growth and expanding economy. The intricate system of reservoirs, canals, and water diversions started in the mountains of western United States during the late 1800's and greatly expanded in the 1930's and early 1940's is an engineering approach to this problem. Another approach is to manage the primary water-producing areas in a way that will enhance streamflow. As part of its national effort to improve yields from wildlands, the research branch of the USDA Forest Service decided to explore the possibilities of improving water yields from alpine areas in the Rocky Mountains. This Paper gives some of the background and summarizes the results from a series of studies carried out in the Colorado Rocky Mountains from 1955 to 1972.

The Rocky Mountain Alpine Zone

Definition and Land Forms

The "alpine zone" is that part of the mountains above the natural limit of erect tree growth. In the Rockies, tree line varies from about 10,000 ft in northern Wyoming to about 12,000 ft in southern Colorado and northern New Mexico. These elevations will vary considerably with local exposures. Land forms vary from broad, gently sloping ridge crests and plateaus to steep-sided rocky peaks and horns, depending primarily on the bedrock geology and the glacial history of the area (fig. 1). Glaciation has been extensive and patterned ground, mass soil movement, and soil frost features are prevalent (Johnson and Billings 1962).

Weather

Weather is often severe in the alpine zone (Judson 1965, Marr 1967). Winds are strong and

Figure 1.—General view of an alpine area in the Front Range of Colorado in late June. Some of the snowfields are in the lee of low trees or in nivation hollows. Others are in the lee of the main ridge crest.

persistent on the ridge crests and summits in all seasons. Summer temperatures seldom reach 70°F, and are usually in the 60°'s F. The thin atmosphere filters out little of the solar radiation and ultraviolet, so clear days have a high radiation input and present serious sunburn problems, especially when there is a fresh snow cover. Winter temperatures are cold with subzero (F) days fairly common in January and February. The alpine, however, does not experience the severe cold (−40 to −50° F) found beneath the inversion layer in high mountain valleys on clear, wind-free winter nights. The combination of cold temperatures and moderate to strong winds develop high wind-chill factors. Over three-fourths of the annual precipitation is in the form of snow. The winds move the snow from exposed places and pile it in deep drifts in all wind-sheltered spots. There is seldom any appreciable winter melt in the alpine, so the snow accumulates all winter and melts in late spring or early summer. Summer rains may be intense, but they seldom persist for long. Graupel (soft hail) and snow can be expected from many summer storms.

Vegetation

Vegetation is predominately grasses, sedges, and a wide variety of forbs and lichen. Tree species are confined to dwarf willow (*Salix* spp.) in the wet spots and to spruce (*Picea engelmannii*), fir (*Abies lasiocarpa*), and on occasion limber (*Pinus flexilis*) or bristlecone pine (*P. aristata*) on the drier sites. Coniferous trees characteristically occur in clumps or islands and are stunted, malformed, and trimmed to streamlined shapes by the wind and blowing snow. The European term **Krummholz** is often used to refer to such trees. The intricate vegetation patterns in alpine areas probably reflect local soil-moisture differences as much as anything. High-elevation westerly exposures tend to be cold deserts, since the winds keep them snow-free all winter and the summer rains quickly percolate through the porous soil or are evaporated by the wind. Plant cover on such sites is mostly prostrate and cushion-type forbs and lichen. Terrain depressions, especially on lee slopes, accumulate blowing snow and are sheltered from the drying winds. Shallow depressions are often boggy areas that typically support willow thickets. Places where deeper snowdrifts develop have such a short growing season that they usually have no more than a sparse cover of snow-tolerant forbs and many are devoid of all vegetation. For more information on alpine vegetation, see Griggs (1956), Paulsen (1960), Marr (1961), Johnson and Billings (1962), and Lewis (1970). Retzer (1962) gives a good discussion of alpine soils for a location in central Colorado.

Streamflow

Runoff data from alpine areas is scarce because there are few gaging stations, and opinions as to the amount of runoff vary considerably. Matthes (1934), for example, said after observing the sun-pitted snowfields at high elevations in the Sierra Nevada and on Mount Rainier that, "these snowfields waste away in the summer because of evaporation and contribute nothing to the streams in the valleys below." Schwan and Costello (1951), on the other hand, state, "the 3.5 percent of the surface area of Colorado in the alpine type accounts for more than 20 percent of all streamflow in the State." Other evidence comes from Lawrence's (1953) study of the Crystal River at Marble, Colorado. This basin, with over 60 percent of its area in alpine or high-elevation meadows or rock slopes, has an average annual runoff of 44 inches with wet years giving 54 inches. Unpublished data from Middle Fork Creek in Alberta[2] showed average annual runoff from this alpine basin to be 23 inches for a 6-year period with a maximum of 27 inches. On the average, streamflow from high-elevation basins peaks in early summer with about 85 percent of the annual flow between May 1 and July 31, and less than 5 percent between December 1 and March 31.

Extent

The extent of alpine type in Colorado, Wyoming, and Utah is not known exactly. Schwan and Costello (1951) estimate there are about 5 million acres in Colorado and Wyoming—about equally divided between the two States—and Lewis (1970) estimates one-fourth million acres in the Uinta Mountains of Utah. Rogers and Braun (1967) say Colorado alone has almost 4.5 million acres. A rough check on U.S. Army Map Service 1-to-240,000 scale maps gave about 1.9 million acres of alpine type in Colorado. Although the exact area of alpine type is not known, it appears to be appreciable. Hence, if techniques could be worked out for increasing the water yield from this already very productive zone, the benefits would certainly be worthwhile.

[2]Personal correspondence in 1972 with R.D. Mays, District Engineer, Inland Waters Directorate, Water Survey of Canada, Environment Canada, Calgary, Alberta.

Basic Approach to the Problem

Snowpack management is the key to water-yield improvement in most areas where snowmelt is the major source of streamflow. This is especially true in the alpine zone where grasses and grasslike species are the only significant vegetation. The possibilities of manipulating the vegetation to improve water yields—a common practice in forested areas (Leaf 1975)—is simply not practical in alpine areas.

Field observations under winter and summer conditions emphasized the importance of wind transport and deposition of snow in the high-elevation sites. The winds pick up snow from exposed places and deposit it in the lee of terrain breaks or other obstacles that provide a wind shadow. As a result, the alpine snow cover is made up of a mixture of deep snowfields and bare spots interspersed in a rather shallow general snow cover. The size and shape of the snowfields vary with the size, shape, and orientation of the barrier behind which they form. The snowfields form in the same places each year and many persist until late summer.

These observations suggested that one promising technique for improving water yields would be to use snowfences upwind of natural snowfields to increase the amount of snow held in these areas until late summer. By locating the fences so the snow they trapped piles on top of that in the natural drift, some of the deeper snowfields could be extended and others could be deepened. This increase in the amount of snow held in deep, high-elevation drifts that persist until autumn should increase the late-summer streamflow from the basin. The additional snow trapped by the fences would normally blow to lower elevation where it melts during early summer—a time of abundant streamflow. Thus, the fences, when used as outlined above, would be expected to change the timing of streamflow and not necessarily to increase total annual water yields.

Experimental Work

Early Studies and Results

An early study (Martinelli 1956) confirmed the idea that drainages with more late-lying snowfields had more late-summer streamflow than nearby drainages with fewer late-lying snowfields (table 1).

Another study (Martinelli 1965a) compared the streamflow from three drainages on the east side of the Front Range in Colorado and confirmed the importance of the alpine zone as a water producer. Both annual and July-August streamflow increased with an increase in the percentage of the total basin in alpine type (fig. 2). The water-yield potential[3] from the alpine snowfields in these drainages varied from 95 percent of total summer flow in one stream with 62 percent of its drainage basin in alpine type to 59 percent for another with only half as much alpine.

Characteristics of the alpine snowfields were studied under summer and winter conditions for several years. Summer data showed early summer snow depths of more than 20 ft (table 2) in the larger snowfields and snow densities of 500 to 600 KgM^{-3}. Higher densities were noted

[3]*Water yield potential was computed from weekly ablation measurements assuming a linear decrease in snow area with time, snow density of 500 KgM^{-3} and zero losses to evaporation, evapotranspiration, and ground water storage.*

Table 1.--Comparison of two drainage basins and their summer streamflow (Martinelli 1956, p. 112-116)

Item	Glacier Creek	Middle Boulder Creek
DRAINAGE CHARACTERISTICS:		
Area above 8,300 ft elevation (mi^2)	25.2	35.5
Maximum elevation on western border of watershed (ft)	14,255	12,500
Most distant point in watershed (mi)	6.75	9.5
Amount of snow, Sept. 30, 1953 (acres/mi^2)	2.5	0.83
STREAMFLOW (percent of annual):		
July 1953	20	20
August 1953	15	8
September 1953	5	2

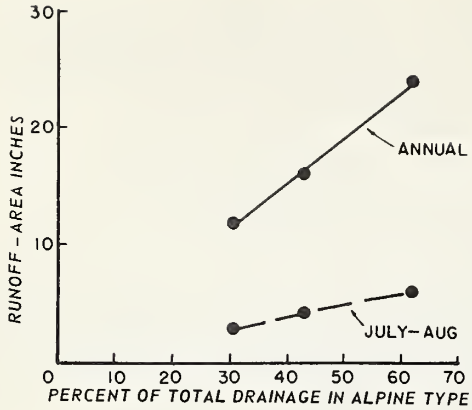


Figure 2.—Area-inches of runoff as a function of the proportion of total drainage area in alpine type in a portion of the Front Range of Colorado (Martinelli 1965a).

Table 2.--Summary of important features of the snowfields studied (Martinelli 1959)

Snowfield, aspect, and elevation	First observation		
	Date	Maximum snow depth	Area
		ft	*Acres*
Mount Evans			
E-- 12,500 ft	June 23, 1955	19.5	3.3
	July 3, 1956	16.7	2.3
	July 3, 1957	--	4.5
	June 26, 1958	--	2.8
Science Lodge			
S-- 11,500 ft	July 1, 1955	21.8	8.6
	June 30, 1956	16.7	8.5
Trail Ridge No. 1			
NE--12,000 ft	July 3, 1955	8.0	.5
Trail Ridge No. 2			
N-- 11,700	July 4, 1955	[1]21.5	3.8
Corona			
N-- 11,500	July 19, 1955	[1]18.8	2.6

during periods of heavy summer rain when meltwater could occasionally be seen flowing over the snow surface for short distances. Free water content in the top 1 ft (30 cm) at midday in August varied from 6 to 11 percent, depending on elevation and aspect of the site. Ablation varied from 1 to 2.8 ft (30-85 cm) of snow per week and averaged 1.9 ft (58 cm) per week for 1955 and 1956 (table 3).

The onset of ablation varies from year to year with variations in spring weather conditions, and the size of the fields varies with winter snow

Table 3.--Average ablation in inches of snow per week for several aspects and elevations, 10 to 80 readings per field (Martinelli 1959)

Month and year	Ablation by elevation and aspect				
	12,500 ft-- E	11,500 ft-- S	11,500 ft-- N	11,700 ft-- N	12,000 ft--NE
	- - - - -		*Inches*		- - - - -
July					
1955	21.6	27.6	[1]28.8	26.4	28.8
1956	18.1	24.0	--	--	--
1957	19.3	--	--	--	--
1958	22.8	--	--	--	--
August					
1955	20.5	28.8	24.0	24.0	--
1956	16.9	25.2	--	--	--
1957	16.9	24.0	--	--	--
1958	[2]24.0	--	--	--	--
September					
1955	[2]16.9	--	[2]18.1	[2]15.7	--
1956	[2]16.9	[2]22.8	--	--	--

[1]Measured first 2 weeks of month only.
[2]Measured last 2 weeks of month only.

amounts. Once spring melt is firmly established, however, the reduction in snowfield area progresses at a remarkably uniform rate, regardless of the time of onset or the initial size of the field (fig. 3).

During the summer it was noticed that frozen ground extended out a short distance from the edge of the snowfields. The depth to the frozen layer increased with distance from the edge of the snow. At times melt water trapped above this frozen layer soaked the soil, giving a fluid mixture that occasionally produced miniature mudflows when disturbed. There was no doubt that the snow was producing considerable amounts of melt water. In some locations, the melt quickly disappeared into the coarse soil so there was little evidence of melt water a slight distance from the fields. Drilling crews working in a tunnel 1,600 ft below one study site reported (telephone conversation) water flowing through the tunnel roof at times that corresponded closely to the seasonal and diurnal production of melt water in the alpine snowfields above. No doubt this deep and rapid percolation of melt water contributed to the idea of heavy evaporation losses mentioned earlier.

It was also noticed that foreign material, such as soil or plant remains on the snow surface changed the melt (fig. 4). This suggested the possibility of altering the melt rate of alpine snowfields to meet management goals.

Winter observations at selected alpine sites helped confirm some of the early concepts. Weekly readings on a series of snow stakes gave

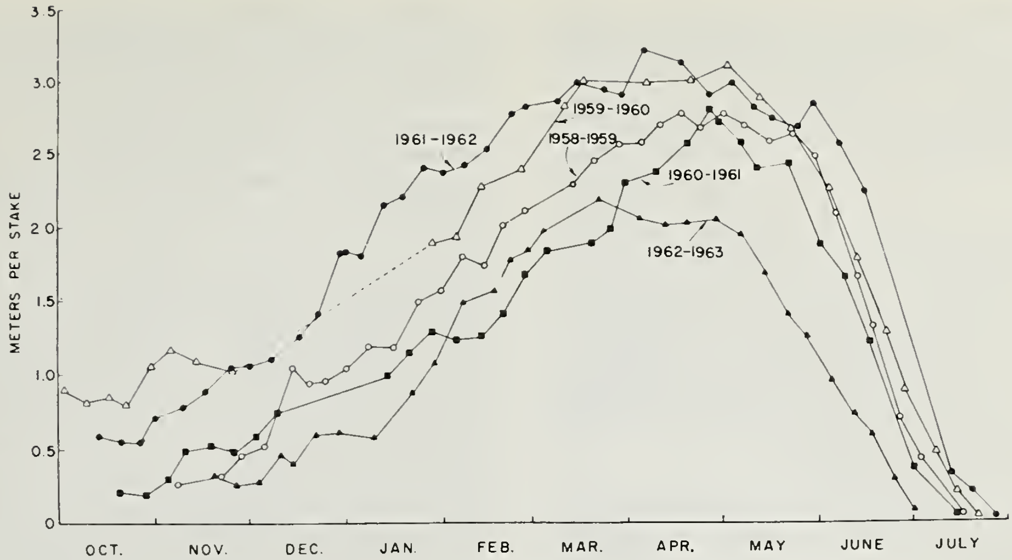


Figure 3.—Snow depths in the control area at Loveland Basin, Colorado, for 5 winters. Each point represents the average snow depth at 29 stakes (Martinelli 1965b).

information on how the alpine snowpack accumulated. The uneven depth of the pack was emphasized with some stakes seldom showing as much as 3 ft of snow, while others nearby would exceed 15 ft most years. The sequence of accumulation was also of interest. Snow accumulated first at the windward edge of the fields and built downwind rather than filling the deeper parts of the field as first casual speculation might suggest. The size and shape of the fields reflected the size and shape of the barrier behind which it formed, with the exception that very heavy or very light snow years made a difference in the size of the field. This indicated that there was insufficient blowing snow to fill some of the fields during dry years. Prior to this, it was generally felt there was enough blowing snow at most alpine sites to fill all but the largest catchments, even in relatively dry years.

Figure 4.—Soil and plant material, blown from the area in the background, accumulated in depressions in the snow. Subsequent melting lowered the surrounding snow cover more rapidly than that protected by the layers of soil, which now appear as soil-capped snow mounds.

The winter stake readings showed most of the seasonal accumulation took place in a relatively few events (table 4). Over a 5-year period, between 55 and 70 percent of the seasonal accumulation was deposited during the 5 weeks of heaviest drifting. Furthermore, between 30 and 40 percent of the seasonal accumulation took place in the 2 weeks of heaviest drifting. For 3 of the 5 years, the first major storm of the season was also the largest accumulation period of the winter. Weekly data are given because that is the way the data were taken and there was no good way to interpolate for shorter periods. In many cases, the weekly accumulation actually took place in a few days, so the true periods of heavy accumulation were even shorter than given here.

Attempts were made to develop snowdrift gages in order to learn more about the time,

Table 4.--Total snow accumulation on 29 control stakes at Loveland Basin, 12,000-ft elevation, for the five major drift periods each year, 1958-63 (Martinelli 1965b)

Major drift period	Accumulation
	ft
1958-59:	
December 5-14	[1]50.5
January 15-23	30.2
February 13-19	26.0
January 30-February 6	21.2
December 31-January 7	16.7
Total, five drift periods	144.6
Total, entire winter	267.42
	Percent of total
Five largest drift periods	54
Two largest drift periods	30
1959-60:	
September 27-October 2	87.0
February 4-13	32.8
October 22-30	24.5
February 24-March 11 (2-week period)	42.5
October 30-November 5	11.0
Total, five drift periods	197.8
Total, entire winter	286.44
	Percent of total
Five largest drift periods	69
Two largest drift periods	45
1960-61:	
December 9-23 (most between 19+23)	45.7
March 25-April 1	40.8
February 19-26	24.7
April 19-26	22.7
November 4-10	17.5
Total, five drift periods	151.4
Total, entire winter	253.45
	Percent of total
Five largest drift periods	60
Two largest drift periods	34
1961-62:	
January 5-12	46.7
September 15-22	43.8
December 22-29	39.6
March 29-April 5	28.0
February 15-23	23.5
Total, five drift periods	181.6
Total, entire winter	286.18
	Percent of total
Five largest drift periods	63
Two largest drift periods	32
1962-63:	
January 28-February 6	39.3
January 9-21	27.3
January 21-28	20.2
December 14-21	18.4
February 16-24	18.4
Total, five drift periods	123.6
Total, entire winter	196.44
	Percent of total
Five largest drift periods	63
Two largest drift periods	34

[1]Figures are total accumulation on 17 check stakes plus 12 stakes in field V. For this date, average accumulation would be 50.5/29=1.74 ft per stake.

duration, and intensity of drifting events. Several versions of storage-type drift gages were designed and tested, as well as one directional recording type. All had serious limitations and were inconvenient and awkward to use. The recording blowing snow gage recently developed by Tabler and Jairell (1971) is a mechanically improved unit that embodies several components of these earlier gages. There are basic problems, however, with all gages that trap blowing snow. It is generally agreed these problems can be avoided only by gages that measure the moving particles without trapping them. The snow particle counter developed in the Station's Alpine Snow and Avalanche Project (Schmidt and Sommerfeld 1969, Schmidt and Holub 1971, Schmidt 1971b) works on a light attenuation principle (Landon-Smith and Woodberry 1965, Sommerfeld and Businger 1965, Hollung and others 1966, Rogers and Sommerfeld 1968) that avoids all the problems associated with traps. It has been shown to be accurate and thoroughly field reliable.

Two other early studies involved field measurements of the rate of **evaporation** and **condensation** at a summer snow surface, and the change in melt rate caused by materials added to the snow. Plastic lysimeters were used to measure evaporation and condensation on a snowfield in North Boulder Creek (Martinelli 1960). There was a net gain of moisture on the snow surface during August one summer. The next July there was a net loss of about the same magnitude due to evaporation (table 5). In both cases, moisture exchange was between 2 and 3 percent of the daily melt. The average rate was +0.03 inch per day in August 1957 and −0.03 inch per day in July 1958. The difference was primarily due to weather conditions during the afternoons, since condensation dominated the nights and evaporation the mornings for both summers. Others (deQuervain 1952, West 1959, Hutchison 1966) have also confirmed this general order of magnitude for moisture exchange at a spring or summer snow surface.

The change in melt rate caused by materials added to the snow surface was studied for one summer (USDA FS 1956). Carbon black, soil, and gravel were added in thin layers to speed melt. Sawdust and soil in 3-inch layers were added to slow melt. After 19 days, the most effective treatments were the sawdust, which reduced melt 50 percent, and the carbon black, which increased it 10 percent. Only the sawdust treatment was statistically significant. The carbon black would have been more effective if it had been spread more evenly. Small patches of concentrated carbon black actually reduced melt rather than accelerated it. The small size (1 m × 1 m) and close spacing of the test plots also reduced treatment effect a bit toward the end of the experiment.

Table 5.--Melt from an alpine snowfield and net moisture exchange between an alpine snow surface and the atmosphere (Martinelli 1960)

Date	Inches per day of water from-- Melt	Net moisture exchange	Days	Containers
			No.	*No.*
SMALL CONTAINERS:				
1957--				
July 30-Aug. 1	1.6394	0.0298	2.00	6
Aug. 6-8	2.2355	.0344	2.12	4
Aug. 13-15	1.2079	.0129	2.00	2
Aug. 21-23	1.8951	.0387	1.96	2
Aug. 28-29	1.0477	.0043	1.00	2
Weighted average	1.6736	.0263		
1958--				
July 9-18	1.5769	-.0268	8.71	3
LARGE CONTAINERS:				
1957--				
Aug. 20-29	2.0798	.0535	8.96	1
Aug. 21-29	2.1163	.0420	8.29	1
Weighted average	2.0973	.0480		
1958--				
July 8-17	1.8336	-.0595	9.08	2

Snowfences for Increasing Summer Streamflow

Since most of the above evidence confirmed the possibility of using fences to improve alpine water yields, a series of fences were built to test the idea more directly. The first fences were common slat and wire fences, 8 to 12 ft tall, located upwind of five natural snowfields at an elevation of 12,000 ft near Loveland Basin ski area in Colorado. These were in a high alpine basin, 0.3 to 0.5 mile east and 500 to 600 ft below the Continental Divide. Later, four more fences were built—three on major ridge crests and one on a windy, exposed lee slope with a gentle gradient.

All fence work was based on the following assumptions:

1. In alpine areas, drifting snow accumulates to great depths only in places that are protected from the wind.
2. Snow fills most terrain depressions before the end of winter. Once full, these areas are aerodynamically smooth and trap little additional snow.
3. There is no shortage of drift snow in alpine regions most years. Therefore, the depth of snow accumulations could be greatly increased if the capacity or the trapping efficiency of natural catchments could be increased.
4. There should be places in alpine regions where barriers of modest height (10 to 12 ft tall) could be combined with terrain features to increase greatly the trapping efficiency of the natural terrain.
5. If snow depths could be increased in areas where it is normally 3 to 5 m deep, the amount of snow available for summer streamflow would be increased substantially.
6. Fence effect can be measured on the basis of changes in the amount of snow in the catchment with and without the fence. Snow depths will be equated to "potential melt-water production."

As a supplement to the alpine fence studies, other snowfence experiments were started at a more accessible site on Pole Mountain, Wyoming, to test certain fence design features. The influence of gap size, new fence materials, and a "swinging panel" design on the size and location of the lee drift were studied at this grassy, windswept site. The swinging panel was an attempt to design a fence that would trap snow effectively at low to moderate windspeeds and would streamline itself during high winds to minimize structural damage. It was not very effective, so the idea was dropped. Several plastic cloth materials were tested to see how they compared to slat and wire fencing. While the cloth fences were lightweight, easy to handle, and worked well, the extra cost and the added installation and maintenance problems argued against them for many sites. Tests on the influence of gap size on the size and location of the lee drift were more productive (fig. 5). Relations were established (figs. 6, 7, 8) between gap size and the location and size of the lee drift (Martinelli 1964).

Other work at this test site (Tabler and Veal 1971) showed that windspeed reduction increased with fence height for fences 6 to 12 ft tall, but that the reduction per foot of height (windspeed reduction efficiency) was greatest for the 6-ft fence. Still other work at this site (Tabler 1968, 1971, 1973) has helped establish economic and physical criteria for designing systems of snowfences to serve a variety of needs in the alpine as well as in other vegetative types.

Results of Alpine Snowfence Studies

Fence Effect on Snow Accumulation

The long-term studies of snowfences at alpine sites showed fence effect varied greatly, even

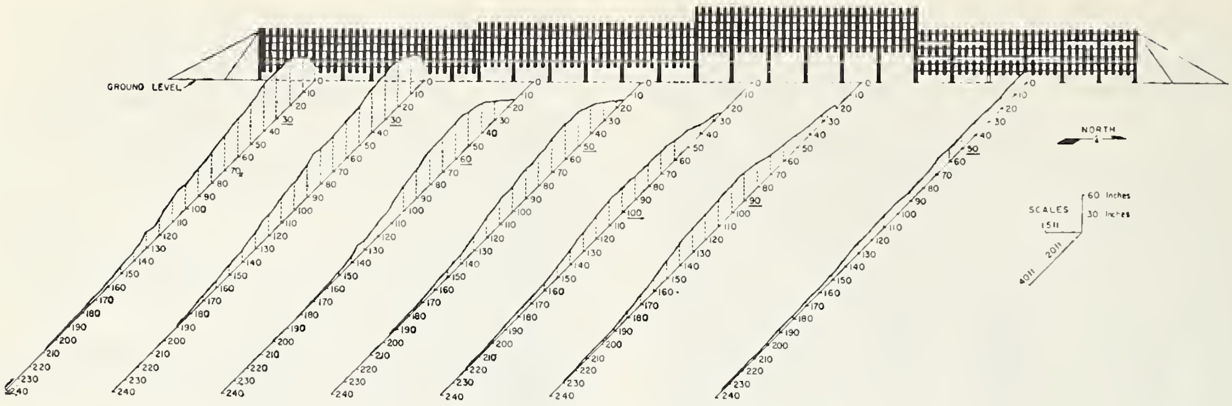


Figure 5.—Typical snowfence panel at Pole Mountain, Wyoming, at the end of the 1962-63 accumulation season. Snow depths along the profile lines are the average for four locations. The underlined figures along the probe lines mark the position of maximum snow depth. The right panel is a special design that swings open in high winds. Other panels are tests of bottom gap size. Note: There are three different scales in the diagram (Martinelli 1964).

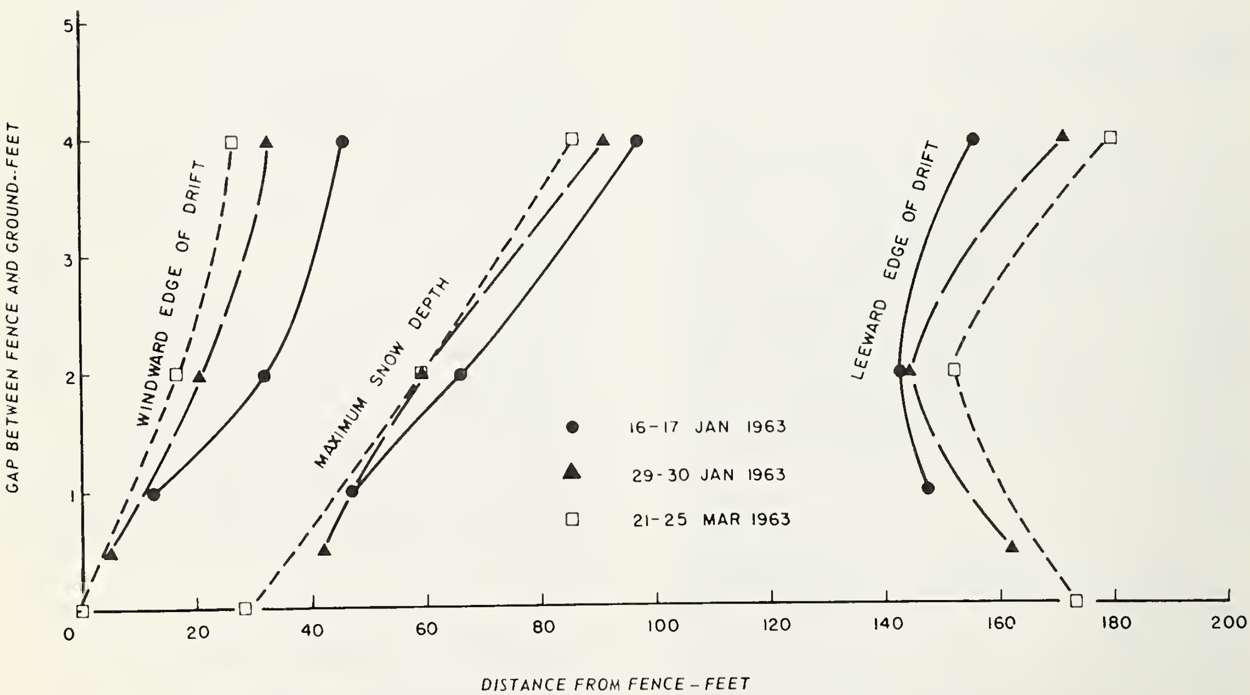


Figure 6.—Effect of size of gap on the snowdrift behind 6 ft of vertical slat snowfencing. Gap widths of 6 inches and 0 represent the gradual closing of the 1-ft gap. Points are the average of two values from each of four locations.

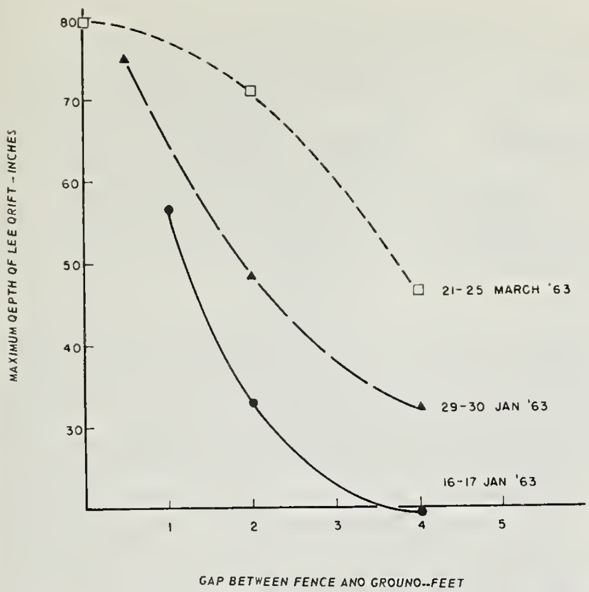


Figure 7.—Maximum snow depth in the drift behind 6 ft of slat snowfencing for various gap widths. Gap widths of 6 inches and 0 represent the gradual closing of the 1-ft gap. Points are the average of two values from each of four locations.

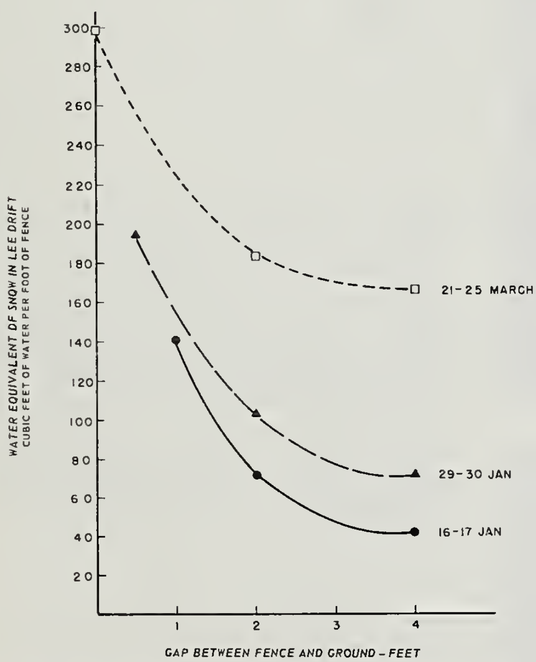


Figure 8.—Water equivalent in the drift behind 6 ft of slat snowfencing for various gap widths. Gap widths of 6 inches and 0 represent the gradual closing of the 1-ft gap. Points are the average of two values from each of four locations.

when sites were carefully selected. At three of nine study locations, fences increased the volume of late-lying snow and prolonged the melt season by several weeks. At one site, the increase in total snow accumulation was accompanied by a more rapid melt rate so that early summer runoff was increased but the melt season was not prolonged. At three more of the sites, snow depths were increased close behind the fences, but were decreased farther downwind with no net increase in the amount of snow, and at two sites the fences reduced the amount of snow caught (table 6).

At the best site, Straight Creek Pass (fig. 9), a fence 10 ft tall with a density of 42 percent and a bottom gap of 2 ft increased the total volume of snow at the start of the melt season by 1,500 ft^3 of snow per lineal foot of fence (ft^3/ft) and increased average depth by 6.5 ft. The snow behind the fence persisted about 3 weeks longer than normal (Martinelli 1973).

Maximum snow depths in the fence-induced lee drift exceeded the height of the fences (H) at most of the catchments. In general, depths varied from 0.8 to 1.5 H, but were as low as 0.5 to 0.7 H at Loveland Basin fields I and III. The deepest part of the positive fence effect was located 3 to 5 H downwind of the fence in most cases. The exceptions were Loveland Basin field II and Straight Creek, where the crests of the lee drifts were 8 to 11 H downwind of the fences.

At the better sites, 60 to 120 ft of fence was needed to produce an extra acre-foot of melt water potential at the start of the melt season. This is based on fences 10 to 12 ft tall, 40 percent fence density, bottom gaps of 2 to 4 ft, and snow density in the lee drifts of 500 KgM^{-3} (Martinelli 1973). At such sites, the melt season was prolonged 1 to 3 weeks. In general, an extra 2 ft of snow depth on July 1 means an extra week added to the melt season.

Based on 10 years of field experience, we found that for our purposes **good fence** sites had:

1. Ridge crest locations with the deep part of the natural drift not more than 8 to 10 H to the lee.
2. Upslope or level windward approach to the fence.
3. Good orientation to prevailing drifting winds.
4. Upslope or level terrain to the lee of the accumulation area.
5. Plenty of contributing area (at least 500 ft).
6. Little natural accumulation upwind of the fence.
7. Northerly to northeasterly exposure (or terrain shadowing of any southerly exposed accumulations.)

Table 6.--Summary of changes in snow accumulation at natural snow accumulation sites after slat and wire snowfences were located at upwind edge of accumulation site

Site	Change in snow accumulation	Change in length of melt season	Change in amount of potential melt water
Straight Creek Pass	Increase	Increase (3 weeks)	Doubled
Mount Evans	Increase	Increase (1 week)	Doubled
Loveland Basin II	Increase	Increase (1-2 weeks)	Increase
Teller Mountain	Increase	No change	Increase
Loveland Basin I	No net change	No change	No change
Loveland Basin III	No net change	No change	No change
Loveland Basin VI	No net change	No change	No change
Loveland Basin IV	Decrease	Decrease (1-2 weeks)	Decrease
Glacier Mountain	Decrease	Decrease (1 week)	Decrease

Figure 9.—Straight Creek Pass snowfield, with a snowfence 10 ft high:
In February, with natural snow accumulation in foreground. Behind the fence, where person is standing, snow deposited by winds blowing from left to right is about 20 ft deep.
In August, the 6 to 7 ft of additional snow due to the fence is still obvious. Snow depth in left foreground is typical of the unfenced portion of this natural drift.

Poor sites had:

1. Downslope approach to the fence.
2. No natural catchment within 8 to 10 H of the logical fence location.
3. Upwind accumulation sites to rob snow or to throw a drift on the fence.
4. Variable wind direction during drifting.
5. Steep downslope exhaust zone that results in reverse windflow and erosion of the lee deposition.

Schmidt (1970) used pressure-gradient concepts to provide a rationale for relating fence and terrain effects to snow accumulation. He points out that the pressure gradient in the lower layers is considered zero for flow over a horizontal surface. However, local pressure gradients develop when air flows over irregular terrain or against natural or artificial barriers, such as trees or snowfences. A favorable pressure gradient exists when flow moves from high pressure to lower pressure; that is, air flowing uphill. An adverse pressure gradient exists when flow is from a lower toward a higher pressure; that is, air flowing downslope or against a barrier. When flow is along a favorable pressure gradient, velocity and shear stresses in the lower layers increase downwind and maximum shear stress is at the surface. When air flows against an adverse pressure gradient, velocity and shear stresses near the ground decrease and maximum shear stresses move up from ground level. Under extreme adverse pressure conditions, a reverse flow (rotor) develops. Since the carrying capacity of the wind is directly related to the shear stresses in the lower layers, when flow goes from a favorable to an adverse pressure gradient, velocities and shear stresses are reduced and snow tends to settle out of the airstream.

Examples of how the above concepts help explain total snow accumulation and maximum drift length observed in several terrain situations are given below (Schmidt 1970):

Case 1—A snow fence on a uniform windward slope.—The adverse pressure gradient associated with the fence is reduced by the favorable pressure gradient created by flow up the windward slope. Thus, the terrain gradient reduces both total drift accumulation and maximum drift length from those expected for a horizontal surface. Figure 10 shows that this is the case for the maximum drift length.

Case 2—A snowfence on a uniform leeward slope.—Here the adverse pressure gradient produced by the fence is added to the natural adverse pressure gradient. A larger fence effect should result in increased drift accumulation and maximum length compared to the horizontal case (fig. 10). For example, a fence 12 ft high with a 3-ft gap was located upwind of a depression in a long lee slope on Mt. Evans in Colorado. The resulting drift had a maximum length on the order of 30 times the fence height with a fairly uniform increase in depth (fig. 11a).

One problem that arises from locating a fence in a natural adverse pressure region is that the fence becomes buried in the drift. This results in expensive maintenance unless the fence is designed to withstand snow settlement load.

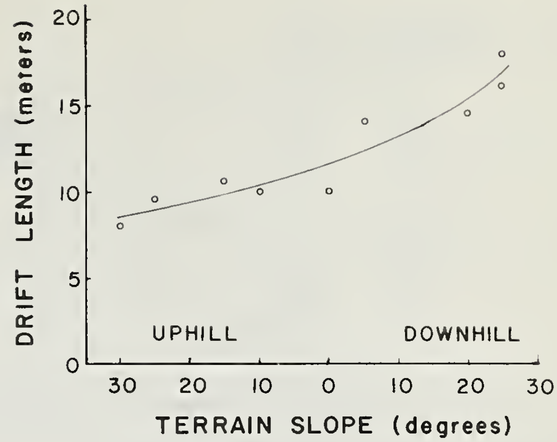


Figure 10.—Maximum drift length as a function of terrain slope (Schneider 1962).

Case 3—A snowfence located leeward from a rounded ridge crest.—The pressure gradient changes from favorable to adverse near the crest. The fence is located in an adverse pressure gradient, and the results depend on the strength of the natural adverse gradient. If the lee slope is gradual and flow does not separate, results should be similar to those of Case 2, where accumulation and length were increased and the fence became buried.

If the lee slope is steep and flow separates, the fence fixes the point of separation, and a cornice forms behind the fence. In this situation, velocities in the reverse flow are strong enough to transport snow. The drift is then shorter and contains less snow than expected for the same fence on a horizontal surface. Such a condition was

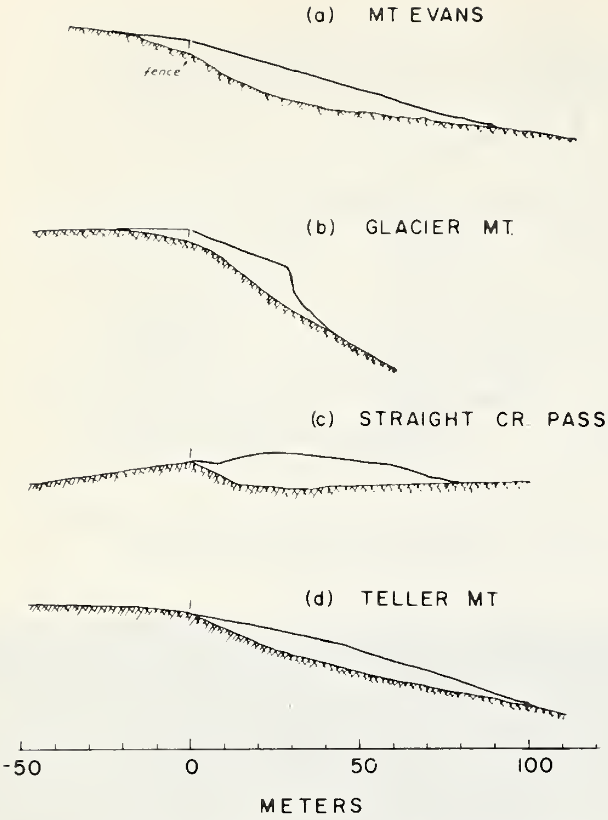


Figure 11.—Snowdrift cross sections on four irregular terrain situations, showing variations of total drift length and snow accumulation (horizontal and vertical scale equal): (a) Case 2—Mt. Evans, (b) Case 3—Glacier Mountain, (c) Case 4—Straight Creek Pass, (d) Case 5—Teller Mountain (Schmidt 1970).

examined at Glacier Mountain near Montezuma, Colorado (fig. 11b). The fence was 115ft (35m) lee of the crest and the lee slope was steep. Again the fence was buried in the drift in spite of the gap between fence and ground.

Case 4—A snowfence at a sharp ridge crest.—If a fence is located at the point where the pressure gradient changes from favorable to adverse, the fence effect is again increased by the natural adverse pressure gradient in the lee of the crest. As in Case 3, the resulting drift depends on the steepness of the lee slope; it is larger and longer if the slope is gradual, and smaller if the slope is steep enough to cause strong reverse flow. However, the favorable pressure gradient upwind of the fence maintains increasing surface shear stress, which causes snow erosion and leaves the fence free of the drift.

The drift cross section shown in figure 11c was measured at Straight Creek Pass on the Continental Divide in Colorado. The terrain depression lee of the crest filled in rapidly, and the lee slope was then gradual enough to allow a rather spectacular drift to develop.

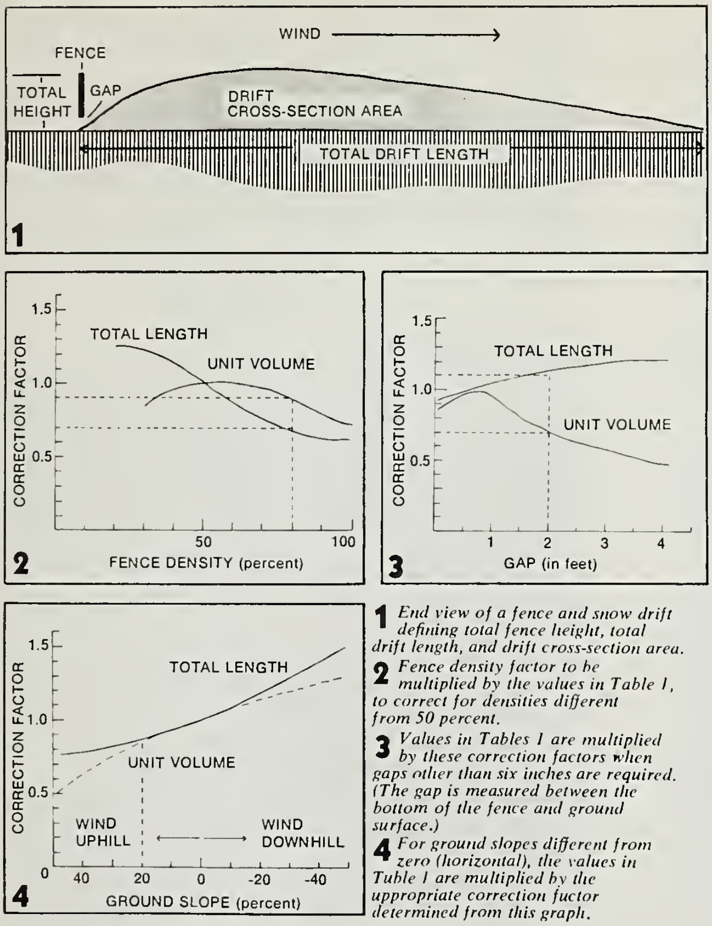
Case 5—A fence located at a break from horizontal to lee slope.—In terms of pressure gradients, this fence is located at a point where the gradient changes from zero to adverse. The fence effect is again strengthened by the natural gradient, and the results depend on the strength of the gradient. A cliff is an extreme example of this case; separation is well defined at the dropoff, and a cornice typically forms. With a more gradual lee slope, both total accumulation and maximum drift length increase. Measurements at Teller Mountain (fig. 11d) are an example of the latter situation.

Although the configurations of terrain and snowfence locations described above are only a few of the infinite possibilities, they suggest a few generalizations to summarize this section: (a) snowfences that obstruct flow in a favorable pressure gradient yield smaller and shorter drifts than expected over horizontal terrain; (b) the effects of fences located at the change from a zero or favorable to adverse pressure gradient should increase as the gradient increases up to the point where reverse flow in the eddy begins to erode the downstream edge of the drift; and (c) fences located within an adverse pressure region should show effects that follow those given in statement (b), but the fences usually become buried in the drift.

A fair approximation of fence effect under a variety of conditions can be obtained by adjusting tabular values of accumulation volumes and drift lengths for level terrain, for slope, fence density, and size of the gap beneath the fence (fig. 12) (Schmidt 1971a).

Some Details on Snowfence Construction

Several things have been learned about building fences in windy sites subject to heavy accumulation. First, every effort must be made to keep the fence from being buried. Snow settlement forces cause extensive damage to any buried fence. Fences designed for long-term projects should be anchored to buried deadmen instead of being guyed. This reduces settlement damage to the fence and creates less clutter



1 *End view of a fence and snow drift defining total fence height, total drift length, and drift cross-section area.*
2 *Fence density factor to be multiplied by the values in Table 1, to correct for densities different from 50 percent.*
3 *Values in Tables 1 are multiplied by these correction factors when gaps other than six inches are required. (The gap is measured between the bottom of the fence and ground surface.)*
4 *For ground slopes different from zero (horizontal), the values in Table 1 are multiplied by the appropriate correction factor determined from this graph.*

Table 1.—Cross-section area and length of drifts formed by fences of various heights.

Total Fence Height (ft.)	Unit Drift Volume* (cu. ft./ft.)	Total Drift Length (ft.)
4	172	64
6	392	96
8	576	128
10	776	160
12	989	192
14	1214	224
16	1470	256

*Drift volume is expressed as the cubic feet of snow storage per lineal foot of fence. It is equal to the drift cross-section area multiplied by one foot of fence length.

Figure 12.—Principles of snowfence design to eliminate an unwanted drift, or to provide snow cover in a particular area, or to accomplish both objectives at the same time (Schmidt 1971a).

around the fence. If some type of wind barrier is needed at a site subject to burial, it is possible a rock wall, earth mound, or some other type of massive structure that could withstand the settlement forces would work better than a traditional snowfence.

Where open structures are used, there is an advantage to using horizontal rather than vertical slats (Tabler, oral communication). The horizontal slat fence has the same density for a wide variety of wind directions, whereas the vertical slat fence presents a higher density to any wind that deviates from the perpendicular. The horizontal openings at the bottom of the fence also act as bottom gaps if snow starts to accumulate at the fence.

There also seems to be some evidence that porous fences of a given density made up of large openings and large solid units are much less effective than other fences of the same overall density that have smaller openings and smaller solid units. For example, a fence with 12-inch-wide slats and 12-inch openings traps much less snow than another fence with 1½-inch openings and 1½-inch slats, even though each has a density of 50 percent. We have no good data on the size of opening where fence efficiency starts to drop off, but it appears to be somewhere between 6 inches and 12 inches.

The back braces on snowfences should attach near the top of the fence. When the attachment is midway or lower on the fence, there is a tendency for strong winds to pull the main fenceposts out of the ground and overturn the fence.

Cautions on Use of Snowfences for Snowpack Management

Before using snowfences, one must decide what the fences are expected to do. In the

studies reported here, the objective was to increase the amount of snow in late-lying, high-elevation snowfields in order to increase late-summer streamflow. In other cases, it may be desirable to use snowfences to increase spring or early summer streamflow, to keep snow out of such areas as avalanche starting zones, highway or railway rights-of-way, parking lots, or selected big-game browsing areas; or to add snow to ski or snowmobile trails, snow roads, or to the area contributing water to stock ponds, or domestic water supplies. Fence location, density, bottom gap, and height can and should be changed, depending on the job the fence is expected to do.

Fences used to increase late-summer streamflow from alpine areas should be located only at selected spots and not strung indiscriminately along entire ridges or upwind of a random assortment of natural snowfields. In addition, snowfences in the alpine area of a watershed should be considered only supplemental to other water-yield improvement treatments in the timbered and riparian zones of the watershed. Care must be exercised to minimize the visual impact of fences in open areas. Wood poles and native lumber blend into the landscape better than metal structures. Quick-rusting metals are better than shiny aluminum or galvanized metal. Any type of fence in the alpine, however, is easily seen from long distances, as are the shadows cast by the fences, and both are objectionable to many people.

Fringe Benefits from the Alpine Snowfence Work

The evolution of the snowdrift meter from various types of cans and traps to an electronic counter is a significant advance. The Schmidt snow particle counter is theoretically sound and reasonably easy to use in the field. If offers the first good opportunity to gather reliable data on the flux of blowing snow. It also provided basic data for the theoretical approach to the sublimation of blowing snow (Schmidt 1972).

The wide variation in the early fence data was one of the incentives for Tabler and others to develop the contributing distance-snowdrift coefficient-fence capacity concept of fence system design that has proven so useful in the recent Wyoming Highway Department fence projects (Tabler and Schmidt 1972, Tabler 1973).

The knowledge of snowdrift patterns behind fences in irregular terrain is also being used by Colorado Division of Game, Fish and Parks in their Junction Butte Wildlife Habitat Improvement Project. In this study, fences will be used to change natural snow accumulation patterns to make more browse available on winter deer range.

Ski areas, too, find fences useful for many purposes. In some places, they provide snow for wind-eroded trails; in other places, they keep unwanted drifts from parking lots, avalanche paths, and ski trails.

Work Still to Be Done

Snowfences and Blowing Snow

Several bits of additional information are needed before complete guidelines can be developed to help land managers decide how efficiently a given area is trapping blowing snow and how much change can be expected from snowfencing.

First, we need to know the amount of blowing snow arriving at various sites in order to determine trapping efficiency. In the past, there was no way of knowing if a large accumulation of snow was due to high trapping efficiency or to unusually large amounts of blowing snow. The modified snow particle counter is expected to give a good measure of blowing snow.

Second, we need more exact information on which combinations of terrain features result in good natural accumulation sites. Schmidt's (1970) pressure-gradient concepts seem a logical starting point for developing such objective criteria based on sound physical concepts.

Third, experimental evidence is needed to sharpen the relationship between weather features and sublimation losses as given in Schmidt's (1972) theoretical model. Changes in sublimation rate due to snow particle size, humidity gradient, and the ratio of particle speed to windspeed needs to be checked.

The culmination of these efforts would be a better expression of the efficiency of various fence and terrain combinations for trapping blowing snow.

Other Snowpack Management Possibilities

Several other techniques for improving water yields from alpine areas should be tested.

- **Terrain modification** offers some interesting possibilities once we get a better feeling for the relative trapping efficiency of various terrain shapes. Many snow accumulation areas could probably be shaped into more efficient configurations with only minor damage to surrounding vegetated areas. Approach and exhaust zones in many places could perhaps be made more favorable by using earth or rock walls to

trap early snows and thus produce the desired shapes for the remainder of the winter season.

• **Intentional avalanching** should be tried in selected spots. Snow could be released from the starting zones and piled in deep layers in the runout zone. If paths were chosen that loaded rapidly and had confined and sheltered runout zones, it should be possible to store the avalanche debris in or near stream channels and to carry a good deal of snow well into the summer.

• **Glacier building** during average to heavy snow years should also be investigated. The extra water stored in this way could then be used during dry years. A gravity system of spraying water from flowing streams into the air at high-elevation sheltered spots during the fall and early winter should result in massive accumulations of ice. This is a very effective way to store water for use at a later date.

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Snowpack management can be an effective means of improving water yields from the already productive alpine type. Due to wind and rugged terrain, the alpine snowpack is characterized by deep snowfields and bare spots. Because snow accumulates in the lee of terrain breaks or other obstacles that provide wind protection, fences upwind of natural accumulation areas effectively trap additional snow. Snowfences can also control blowing and drifting snow on highways and in avalanche-prone areas. Factors that influence the efficiency of snowfences are: (1) height, (2) density and length of fence, (3) bottom gap, (4) length and maximum depth of lee drift, (5) cumulative effect of a set of tandem fences, (6) vertical alinement, (7) terrain effects, and (8) contributing distance.

Keywords: Alpine zone, water yield, snowfences, snowpack.

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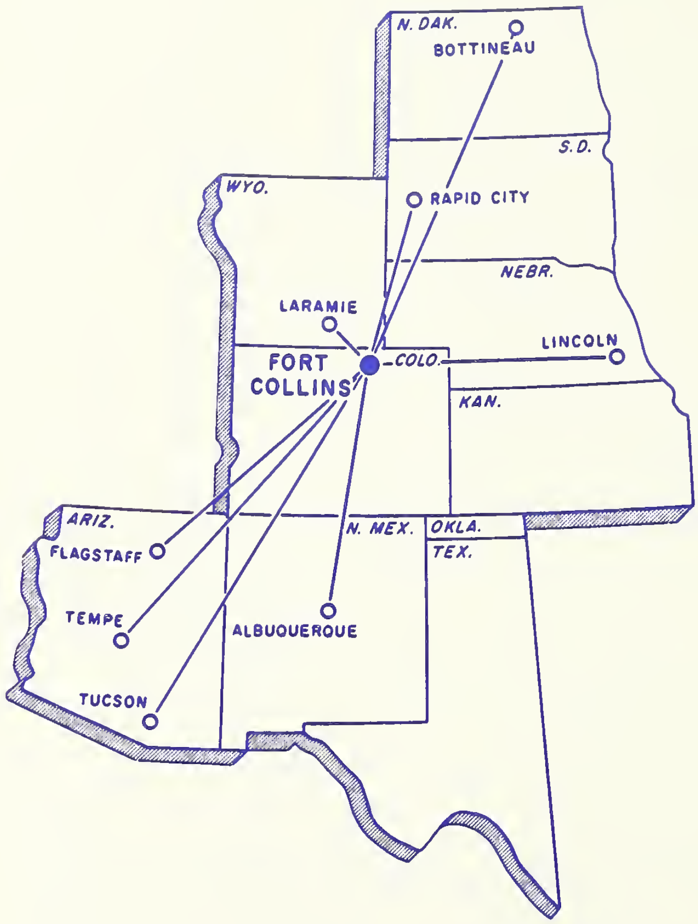
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